PATENT SPECIFICATION

1,068,272

DRAWINGS ATTACHED.

1,068,272

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Int. Cl.:—H 03 b 3/12.

COMPLETE SPECIFICATION.

High Stability Gas Cell Frequency Standard.

We, STANDARD TELEPHONES AND CABLES LIMITED, a British Company, of Connaught House, 63 Aldwych, London, W.C.2, England, (assignees of MAURICE ARDITI), do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to gas cell atomic clocks or frequency standards and particularly to an improvement therefor which provides a narrow resonance line width, and when employing optical pumping, eliminates frequency shifts caused by the pumping light, thus resulting in greater stability.

In general the broadening of the inherent atomic or molecular resonance line in a gas cell is produced mainly by the thermal velocity of the atoms or molecules with respect to the direction of an applied r.f. field, which is known as the Doppler effect. Reduction of this effect can be obtained by the use of non-magnetic buffer gases.

Atomic clocks incorporating alkali vapour gas cell frequency standards have utilized optical pumping and detection of energy transitions which produce the characteristic spectral resonance line at a fixed frequency. However, the buffer gases in the cell cause a shift in frequency corresponding to their pressure and an additional shift is produced by light intensity variations of the pumping lamp. Thus, these atomic clocks do not represent an absolute standard but have been used as secondary standards which change slightly with time due to the light variations. Gas mixtures can be prepared to reduced sensitivity to pressure and temperature, while special optical filtering or high pressure buffer gases can minimize light shifts, but it has not been possible to achieve all of these desired results in one device.

[Price 4s. 6d.]

The ultimate line width in a gas cell is limited by the thermal collisions between atoms or molecules. Atoms fed into a gas cell and having relaxation times greater than their mean time in the cell envelope can, however, be subjected to more than one r.f. pulse and the resonance line then has a width characteristic of the pulse repetition frequency which can be made several times smaller than the natural line width therein. A discussion of related theory and prior art may be found in articles by N. F. Ramsey, Physical Review, 1950, Vol. 78, page 695, concerning atomic beam techniques and by H. M. Goldenberg et al, Physical Review Letters, 1960, Vol. 5, page 361, in connection with gas cells. In the present invention use is made of the phenomenon which, following Goldenberg, may be described briefly as follows.

A gas cell within a resonant cavity operating in the TE_{01} mode contains atoms which will emit a r.f. spectral line at the cavity resonant frequency. A pulse of r.f. energy of this atomic transition frequency is fed into the cavity, causing precession of the electron spin of the atoms, which continue to radiate after the r.f. excitation has been turned off. If now a second, phase coherent, pulse of r.f. is applied to the atoms which are still precessing, at the end of this second pulse further emission will occur, with a much reduced line width, characteristic of the pulse repetition frequency. When the carrier frequency of the r.f. pulses is varied slowly, with a period long compared to the pulses repetition frequency, so that the carrier frequency is swept over a band centered about the line frequency, a plot of the amplitude of the stimulated emission in the cavity as a function of frequency will trace out a resonance curve for the spectral line concerned. Whereas

the resonance curve for the emission following the first pulse is of normal shape, with, perhaps, some small secondary peaks, that for the stimulated emission following the second pulse is found to have an oscillatory pattern of narrow lines contained within an envelope corresponding to that of the resonance curve for the emission following the first pulse. This pattern is known as a Ramsay pattern and will be referred to as such herein.

In accordance with the present invention there is provided an atomic clock controlled by means of a radio frequency line corresponding to a transition between hyperfine magnetic levels in the ground state of an alkali metal vapour, hydrogen or ammonia contained in a gas cell within a resonant cavity, the atoms in the gas cell being optically pumped by a succession of light pulses and interchanging energy with a succession of r.f. pulses which are phase coherent pulses of radio frequency waves whose frequency is controlled by the said line, wherein the light pulses and the r.f. pulses are such and are interrelated in such manner that, after interaction with a first r.f. pulse, the atoms are stimulated to emit the said line in the absence of pumping light and, while still in darkness, are subjected to a further r.f. pulse or, the first r.f. pulse being sufficiently long to permit diffusion of excited atoms into regions of the gas cell subject to different intensities and phase of the r.f. field in the cavity, to a later portion of the same pulse, so as to emit one of the lines of a Ramsay pattern of fine lines having an envelope corresponding to that of the line emitted in response to the first r.f. pulse, or the first portion of the r.f. pulse, respectively, a local oscillator for generating the r.f. pulses being locked to the Ramsay pattern line by means of the r.f. output from the resonant cavity.

In order to improve the signal-to-noise ratio of the detection of the stimulated emission signal, optical pumping is used in the gas cell to increase the change in population distribution of the atoms in the two stable energy levels between which a transition takes place. A continuous pumping light would have the effect of shortening the relaxation time of the atoms and of introducing phase incoherence between the two induced microwave pulses, through optical excitation of the precessing atoms. A careful timing of a pulse sequence of light and microwave is thus necessary to conserve phase coherence and to obtain a spectral pattern with well-defined maxima. If the pulse of resonant light is terminated before the radio frequency pulse is turned off, the longer lived atoms are left precessing in the dark and the second r.f. pulse can be applied. As a result, a larger signal-to-noise ratio and relaxation time can be obtained. Since detection of the microwave stimulated emission takes place when the pulse of light is off, light shifts of frequency are eliminated.

In embodiments of the invention the detection of the stimulated emission is obtained through a microwave receiver coupled to the resonant cavity containing the gas cell. A small modulation of the frequency at a low rate is applied to the r.f. carrier waves of the exciting pulses, with the modulation envelope appearing at the output of the receiver detector. The light pulse and first and second r.f. pulses are repeated in sequence to produce an integrated modulated signal. By comparing the phase of the latter signal with that of the reference modulation in a phase detector and feeding back the error signal to a crystal oscillator, the oscillator is locked to the resonant frequency of the gas cell.

The invention will further be described with reference to the accompanying drawings, in which:

Fig. 1 is a block diagram of an embodiment of the invention.

Fig. 2 shows various pulse patterns as they would appear in related portions of the circuit; and

Fig. 3 represents response curves of the system to different r.f. pulses.

As shown in Fig. 1, a glass cell 10 containing Rubidium 87 is optically pumped through a Rubidium 85 filter cell 12. The filter cell is necessary only when an emission condition or maser action involving population inversion in the Rb 87 is employed. Without the filter cell, the Rb 87 cell acts as an absorption cell. In both cases stimulated emission can be obtained at the end of the microwave pulse and the method is applicable for a frequency standard in absorption or emission conditions. In addition, other alkali atoms such as hydrogen, potassium, sodium or caesium may be used directly in the gas cell without a filter cell. Similar use of an ammonia molecule gas cell is also feasible. A non-magnetic buffer gas such as neon, argon, other noble gases or nitrogen, hydrogen or mixtures thereof, is generally included in the cell to further reduce line width, increase efficiency of optical pumping and to reduce the sensitivity of frequency to thermal effects. The gas cell is placed in a microwave cavity 14 which is excited at a characteristic frequency corresponding to the known energy separation of the hyperfine levels of the vapor in the ground state. Since the 0—0 hyperfine transition used here is magnetic, it can be induced only when the magnetic lines of force H_0 of the r.f. field are parallel to any existing d.c. magnetic fields. A TE_{011} mode cavity is therefore used, with the axis parallel to a constant homogeneous magnetic field of the order

of a few tenths of an oersted in the region of the cell. The microwave frequency is obtained by multiplication of a predetermined submultiple frequency from a stable crystal oscillator 16 up to 60 megacycles at multiplier 17, and desired harmonics are generated by a varactor diode 18 up to the characteristic 6834 mc frequency. A small low rate modulation of the frequency is obtained by applying the output of a modulator 19 to phase modulate a low frequency stage 20 of the multiplier chain. An amplifier 21 in series with the multiplier chain is gated by pulses coming from oscillator 22 and permits the microwave energy to be delivered in pulses of various length and timing sequences, without losing the phase-coherence in successive pulses.

The detection of the microwave stimulated emission at the end of the r.f. pulse is obtained through a microwave superheterodyne receiver coupled to the cavity. The signal is combined with that of local oscillator 23 in a mixer stage 24 such as a balanced silicon diode circuit, to provide a 60 mc intermediate frequency which is fed to an i.f. amplifier 26. To avoid saturation, a gated amplifier 28 turns off the receiver during the time that the initial large microwave pulse is sent into the cavity. The bandwidth of the amplifiers is such that the circuit time constant is small enough not to interfere with the exponential decay waveform of the amplified signal, which waveform corresponds to the decay of the microwave stimulated emission in the gas cell following the pulse. A second mixing is provided with a local oscillator 30 at 60.1 mc, with the resultant 100 kc carrier from mixer 32 being amplified and detected in circuit block 34. Double detection aids in narrowing the bandwidth and improving the signal-to-noise ratio. The output of the amplified-detector is then fed in two separate channels, each of which can be gated independently to select either the output at the end of the first r.f. pulse or that after the second r.f. pulse. The need for two such channels will be discussed in further detail hereinafter.

The output of gates 38, 40 is passed through respective integrating circuits 42, 44 to reconstruct a sinusoidal signal which is then fed to corresponding phase detectors 46, 48 wherein the reference voltage is derived from the low frequency modulator 19 which also acts on the microwave carrier to provide the small frequency modulation at a low rate. The error signal from the phase detector is applied through a switch 51 controlled by a timing relay 50, the operation of which will be more fully discussed hereinafter, and a suitable feedback servo loop 52 which tunes a capacitor 36 to control the frequency of the crystal oscillator 16. The resonant light 54 used for optical pumping is also pulsed in synchronism with the pulse oscillator 22 by using an additional pulsed r.f. oscillator 56 to excite the gas discharge, or in another form a motor driven shutter wheel may be synchronized with oscillator 22 to control the light pulses.

Fig. 2 shows the sequence and position of the various r.f. and light pulses and corresponding gated outputs of the receiver. A basic repetition rate is established for the microwave pulses A with the frequency of the light pulses B being set at half this rate. For convenience in following the preceding description of the Ramsay pattern phenomenon, we refer to the several r.f. pulses as first pulses and second pulses, respectively. Each light pulse must then end before the termination of a first r.f. pulse and the next light pulse must not start before the end of the time allowed for sampling the stimulated emission following the succeeding second r.f. pulse; the duration of the light pulses is thus less than the period between two r.f. pulses. When the atoms have sufficiently long relaxation times, the stimulated emission produces a signal at the output of the 100 kc/s amplifier detector 34 in the form of exponentially decaying pulses C and D. The pulses C are all shown of the same shape and all the pulses D are shown equal in amplitude; this ignores the effect of the low frequency modulation of the r.f. carrier waves forming the r.f. pulses. Due to the low frequency modulation, if the local oscillator 16 is locked on to one side of the atomic resonance curve, where the resonance curve is approximately linear, the successive pulses C and D have, in fact, a superimposed sinusoidal amplitude modulation. Gates 38 and 40 pass only the initial portions of each pulse C or each pulse D, respectively, and include means for opening only on alternate gating pulses. For purposes of comparison with the pulses C and D, and in the absence of l.f. modulation, the pulses from gates 38 and 40 are shown combined at E and F. The actual outputs of these gates, taking the l.f. modulation into account, are shown separately at G and H, respectively. These outputs are fed to respective integrators 42 and 44 which feed the resultant sinusoidal signal, shown in chain lines in Fig. 2, to phase detectors 46 and 48, respectively. Here the integrated outputs of gates 38 and 40 are compared with a phase reference signal from the l.f. modulator 19 and provide respective error signals for the feedback servo loop 52 to correct the frequency of the crystal oscillator 16. To provide suitable error signals at least four to five sampling pulses are required during one period of the modulation.

For the purposes of locking the oscillator 16 to the desired Ramsay pattern line, the

amount of l.f. modulation of the r.f. waves supplied to the resonant cavity need by very small. Were it made larger, so that a wider r.f. band were swept through, the integrated outputs of gates 38 and 40, over a complete cycle of the l.f. modulation, would be as sketched in Fig. 3 at (A) and (B) respectively, and would correspond to the complete resonance curves of the stimulated emission in respect of the first and second r.f. pulses.

It is seen that the curve I resulting from the first pulse has a broad well-defined maximum, while the second pulse produces a curve J with several maximum and minimum variations (the Ramsay pattern) within an envelope corresponding to the first curve. A narrow first response curve thus reduces the number of peaks in the second curve. The half-amplitude line width of the response curve I is very closely equal to $^1/t$, where t is the duration of the microwave pulse A, while the distance between oscillatory peaks in curve J is equal to the inverse of the time interval T between the microwave pulses. Since the output of gate 40 provides a curve having much narrower line widths than that of gate 38, the output of phase detector 48 may be utilized advantageously for locking the crystal oscillator to the particular atomic resonance peak.

With several peaks being present in curve J, it is necessary to provide a method for consistently selecting the same peak to avoid ambiguity. This may be achieved by timing relay 50 which, when energized by power supply 58, first connects the output of phase detector 46 to the servo loop 52 to lock the crystal to the well defined first frequency f_1 of curve I. After a predetermined time, the relay then switches to connect the output of phase detector 48 to the servo which locks the oscillator to the resonant peak frequency f_2 of curve J nearest to f_1. Suitable adjustments of pulse widths and repetition rate can be made to select the desired peak without ambiguity. During the switching interval the time constant of the servo maintains the crystal at the first frequency and thereafter the relay and crystal remains in the second frequency position until power is shut off. Other suitable coarse-to-fine automatic tuning systems may similarly be utilized.

In the event of a sudden frequency change of the crystal oscillator, it is possible, due to the time constant of the servo, that the frequency could be locked at a point other than the desired peak. In order to avoid this error, a second integrator 60 may be connected to gate 38 to provide only even and predominantly second harmonics of the modulation frequency. This is used as a monitor of signal strength to emphasize the differences between peaks and select the optimum point for correct locking. The second harmonic is amplified, filtered and fed to the time relay. If the signal drops below a preset level, the relay is activated and the original switching sequence is repeated. This will occur if the signal is weak or the frequency of the crystal does not correspond to the resonance frequency f_1. Thus, an accidental lock to a peak frequency other than f_2 will be prevented.

As has been emphasized above, the widths of the frequency peaks of the response curve J does not depend upon the width of the microwave pulse, but is dependent directly upon the spacing between pulses. This spacing must be accurately controlled to maintain the desired fixed frequency as a high stability standard. However, the present device can provide a repetition frequency from the crystal oscillator many orders of magnitude more accurate than required to maintain precise timing, through a frequency synthesizer 62 fed by the crystal oscillator 16, and controlling the pulse forming oscillator 22. Thus the same oscillator that is controlled by the atomic transition also provides the necessary accuracy for the timing of the pulse. An accuracy of only one part in 10^3 is required of the frequency synthesizer 62, while the crystal oscillator 16 may be controlled to one part in 10^{12} by the atomic transition. It is also necessary to prevent illumination of the Rb 87 cell by resonance light between the two microwave pulses, as even a small amount of resonance light would inhibit the formation of the desired Ramsay pattern line at the end of the second pulse. The light causes phase-incoherence between the two induced pulses through excitation of the precessing atoms to high energy levels.

A further variation of the system may utilize only one extended pulse in place of two coherent pulses, when the time interval between pulses is sufficiently long for the relaxation to destroy the interference between successive pulses. As explained in connection with Figs. 2 and 3, near the value of t at the optimum signal, the full line width at half-maximum of the response curve I is approximately $^1/t$. Secondary peaks decrease rapidly as the frequency moves from the resonance point. It has been found experimentally, however, that secondary maxima and minima, similar to the pattern of curve J, appear more prominently with only one initial pulse of a longer duration. In this case the distance between secondary peaks corresponds closely to $^1/T$. This effect is thought to be due to the diffusion of the oriented atoms to different parts of the gas cell having different intensities and phases of the r.f. field. Thus sufficient time is provided so that the atoms appear to be sub-

jected to an equivalent second pulse and a Ramsay pattern line is again introduced.

A practical device of sufficient accuracy and signal-to-noise ratio has been made to work accordingly with a single pulse of longer duration. Thus, in the schematic diagram of Fig. 1, gate 40 would not be necessary, with only the output of gate 38 being utilized to lock the oscillator frequency to one of the peaks. Saturation of the receiver is again prevented by maintaining a cut-off state until the end of the input pulse. The optimum peak resulting from the stimulated emission may now be selected manually, with the servo loop open, by direct observation of amplitude when sweeping the oscillator frequency and closing the loop at the desired peak. This can also be done automatically by a circuit which counts the number of times the amplitude passes through a maximum and closes the loop when the selected peak is reached.

Although the embodiment of Fig. 1 uses a sequence of only two microwave pulses to achieve a line width reduction, a sequence of three, four or more radio frequency pulses could be used to reduce the line width further. This will be conditioned by the relaxation time of the atoms in the gas cell, which has to be larger if the number of pulses in the sequence is increased. In all cases, no light pulses should be produced between the end of the first r.f. pulse and the end of the sampling pulse following the last r.f. used in the sequence, in order to conserve phase-coherence between successive pulses. For practical systems, however, the effective line width reduction produced by more than two coherent pulses may be limited by the signal-to-noise ratio of the detection.

It may thus be seen that the present invention provides significant advantages over conventional gas cell frequency standards using optical detection methods. Light intensity variations have no effect as detection by the microwave receiver is now accomplished with the light off. Since there is no light shift, it is not necessary to use a buffer gas of high pressure. This in turn reduces the temperature shift which is proportional to the gas pressure and very low temperature coefficients are obtained. The method is also applicable to other alkali metal vapors such as hydrogen, potassium, sodium or caesium. The latter gas, particularly, is useful due to a higher operating frequency which can result in still greater long term stability and smaller sized apparatus. The use of caesium was previously inhibited by difficulties in reducing light shift. Another improvement is the provision of very narrow resonance lines. of the order to 10 cps or less, which permit greater accuracy and short term stability. The signal-to-noise ratio is greater since it is not necessary to detect a small modulation of a large carrier signal. Only the microwave stimulated emission signal is detected, in the absence of the microwave pulse, and full use of the receiver sensitivity can be made without adjusting delicate microwave bridge balancing. Since the resonant frequency does not depend upon the microwave pulse length or amplitude, but only on the repetition frequency, which can easily be maintained constant by deriving a timing pulse from the locked crystal oscillator, a high degree of accuracy is achieved, with a stability of one part in 10^{11} or 10^{12} being attainable. In addition, frequency pulling by the tuning cavity is extremely small. However, since it is a practical necessity to calibrate the frequency of the peak to which the crystal oscillator is locked against a primary frequency standard, the system should be considered as a secondary rather than an absolute standard.

WHAT WE CLAIM IS:—

1. An atomic clock controlled by means of a radio frequency line corresponding to a transition between hyperfine magnetic levels in the ground state of an alkali metal vapour, hydrogen or ammonia contained in a gas cell within a resonant cavity, the atoms in the gas cell being optically pumped by a succession of light pulses and interchanging energy with a succession of r.f. pulses which are phase coherent pulses of radio frequency waves whose frequency is controlled by the said line, wherein the light pulses and the r.f. pulses are such and are interrelated in such manner that, after interaction with a first r.f. pulse, the atoms are stimulated to emit the said line in the absence of pumping light and, while still in darkness, are subjected to a further r.f. pulse, or, the first r.f. pulse being sufficiently long to permit diffusion of excited atoms into regions of the gas cell subject to different intensities and phase of the r.f. field in the cavity, to a later portion of the same pulse, so as to emit one of the lines of a Ramsay pattern of fine lines having an envelope corresponding to that of the line emitted in response to the first r.f. pulse, or the first portion of the r.f. pulse, respectively, a local oscillator for generating the r.f. pulses being locked to the Ramsay pattern line by means of the r.f. output from the resonant cavity.

2. An atomic clock as claimed in claim 1 wherein the duration and timing of the light pulses and of the r.f. pulses is controlled by the said local oscillator.

3. An atomic clock as claimed in claim 1 or 2 wherein the Ramsay pattern line is emitted in response to a further r.f. pulse and means are provided for temporarily

locking the said local oscillator, for coarse tuning purposes, to the line emitted in response to the first r.f. pulse instead of to the Ramsay pattern line.

4. An atomic clock as claimed in any preceding claim wherein the output of the said local oscillator is frequency modulated by a low frequency modulator, the stimulated emission within the resonant cavity is sampled at least four times during each period of the frequency modulation while the gas cell is not illuminated by the pumping light, the sampling being effected by gating means selecting a pulse of the stimulated emission immediately after each r.f. pulse, and in the case where a Ramsay pattern line emitted during a later portion of the same pulse is used, again during this later portion, the selected pulses are subject to carrier frequency changing and amplitude detection, and the resultant amplitude modulated pulses are integrated to provide a sinusoidal output which is compared with a phase reference signal from the low frequency modulator to provide an error signal for controlling the said local oscillator.

5. An atomic clock as claimed in any preceding claim wherein the stimulated atoms in the gas cell are atoms of rubidium 87 and the optical pumping light is generated by a gas discharge in rubidium 87 and is filtered through rubidium 85.

6. An atomic clock as claimed in any one of claims 1 to 4 wherein the stimulated atoms in the gas cell are atoms of caesium.

7. An atomic clock substantially as described herein with reference to the accompanying drawings.

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Chartered Patent Agent,
For the Applicants.

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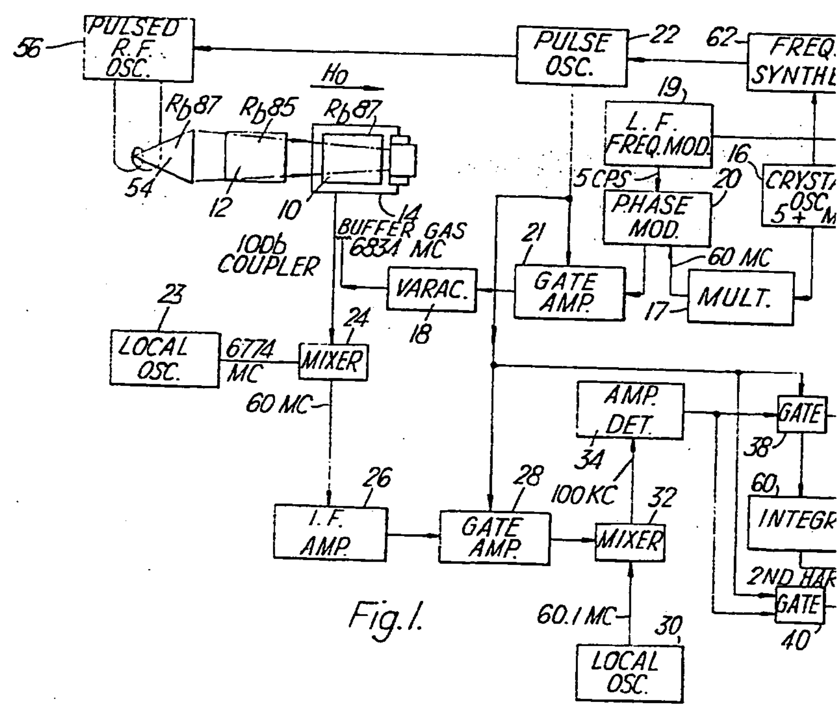

PULSED R.F. OSC.
56
PULSE OSC.
22
62
FREQ. SYNTHE
19
L. F. FREQ. MOD.
16
CRYST OSC 5 + M
5 CPS
20
PHASE MOD.
Ho
Rb87
Rb85
Rb87
54
12
10
14
BUFFER GAS
6834 MC
10Db COUPLER
21
GATE AMP.
60 MC
MULT.
17
VARAC.
18
23
LOCAL OSC.
6774 MC
24
MIXER
60 MC
AMP. DET.
GATE
38
34
60
INTEGR
100 KC
32
26
I. F. AMP.
28
GATE AMP.
MIXER
2ND HAR
GATE
40
60.1 MC
30
LOCAL OSC.

Fig. 1.

1068272 COMPLETE SPECIFICATION

2 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 1

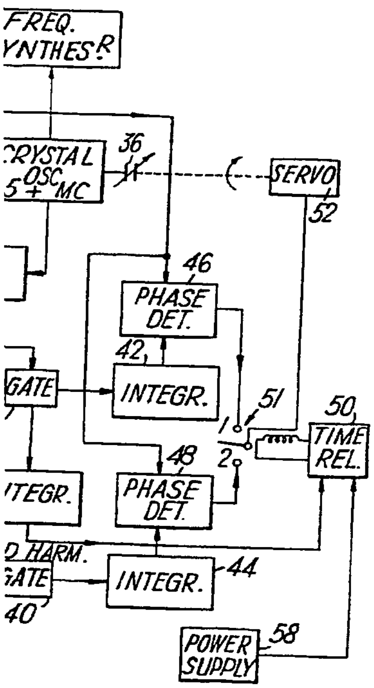
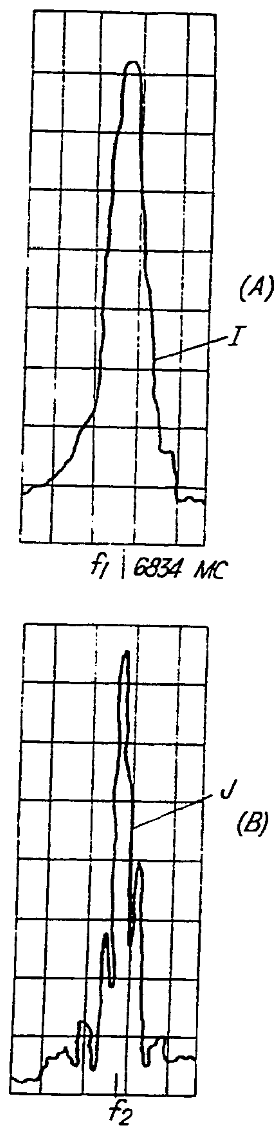


Fig. 3.



1068272 COMPLETE SPECIFICATION
2 SHEETS This drawing is a reproduction of the Original on a reduced scale
Sheet 1

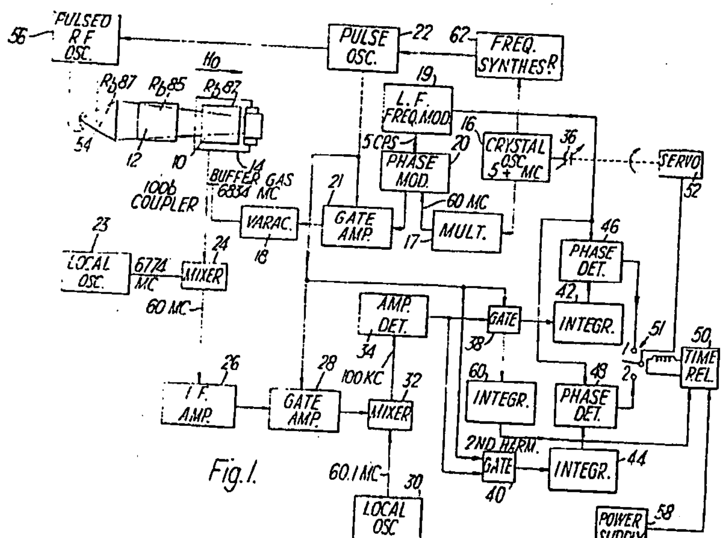


Fig.1.

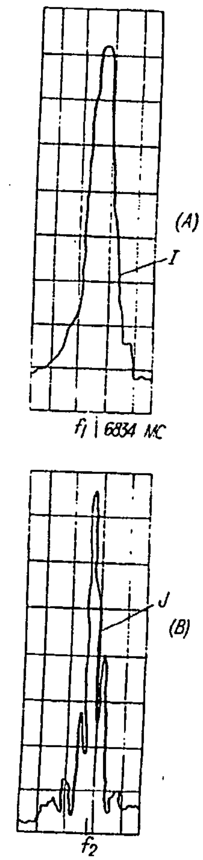


Fig.3.

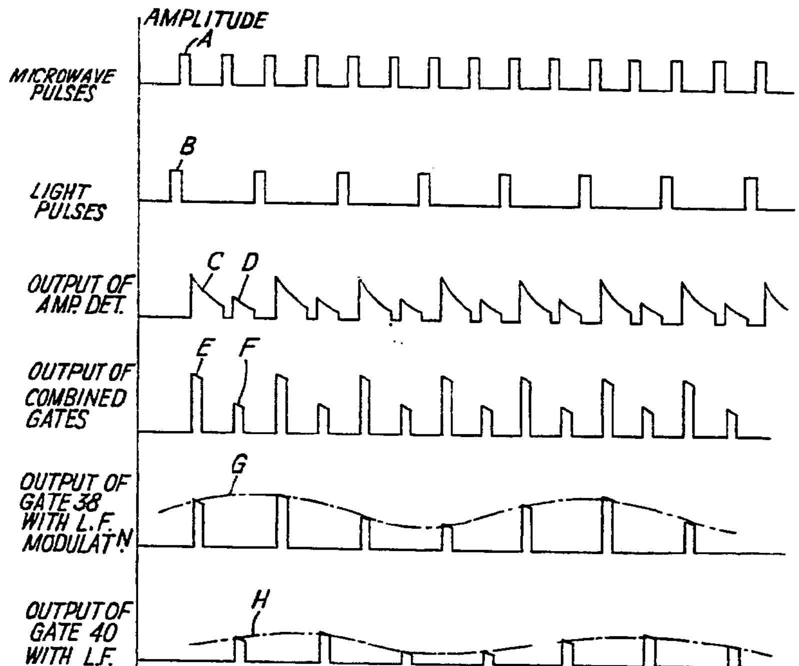

AMPLITUDE
A
MICROWAVE PULSES
B
LIGHT PULSES
C
D
OUTPUT OF AMP. DET.
E
F
OUTPUT OF COMBINED GATES
G
OUTPUT OF GATE 38 WITH L.F. MODULATN.
H
OUTPUT OF GATE 40 WITH L.F. MODULATN.

Fig. 2.